

Robust Preparation of GHZ and W States of Three Distant Atoms

Chang-shui Yu, X. X. Yi, He-shan Song,* and D. Mei
*Department of Physics, Dalian University of Technology,
 Dalian 116024, China*
 (Dated: February 1, 2008)

Schemes to generate Greenberger-Horne-Zeilinger (GHZ) and W states of three distant atoms are proposed in this paper. The schemes use the effects of quantum statistics of indistinguishable photons emitted by the atoms inside optical cavities. The advantages of the schemes are their robustness against detection inefficiency and asynchronous emission of the photons. Moreover, in Lamb-Dicke limit, the schemes do not require simultaneous click of the detectors, this makes the schemes more realizable in experiments.

PACS numbers: 03.67.Mn, 03.65.Ud, 42.50.Ct

Entanglement shared by distant parties can be employed not only to test quantum nonlocality, but also is an important physical resource in quantum information processing (QIP) [1-3]. Although most of the quantum information protocols concern with bipartite systems, multipartite entanglement has also attracted increasing interest since its potential applications in QIP. It has been shown [4] that there exist two inequivalent classes of multipartite entangled states, i.e., Greenberger-Horne-Zeilinger (GHZ) [5] state and W state [4], which can not be converted to each other by local operations and classical communications (LOCC) and show different behaviors if one qubit is traced out. Both classes of entangled state have been shown to have valuable applications in QIP such as quantum teleportation [6,7], quantum secret sharing [8,9], quantum dense coding [10], quantum cloning machine [11] and so on.

Numerous theoretical proposals [12-16] have been proposed and many experiments [17-20] have been conducted to generate GHZ states and W states. It has been shown that to entangle distant atoms (or ions) by using the effect of statistics of distinguishable photons is an effective scheme. For example, in Refs. [21-23], the authors have presented schemes to entangle two distant qubits based on the indistinguishability of particles; Zou et al. [12] have proposed schemes to generate GHZ and W states of four separate qubits by different setups; Fidio et al. [13] have also given an approach to prepare W-type states of three distant atoms; Duan et al. [14] used the analogous approach to prepare entangled states of N atoms. The approach based on indistinguishability was shown to have a lot of advantages, among them the robustness is the most distinct one. In this brief report, we propose schemes to prepare GHZ and W states of three *distant atoms* based on the indistinguishability of their emitting photons. The schemes have been shown to be so robust that the influences of the inefficient detections, the asynchronous emission of photons have no much effects on the fidelity of the prepared W and GHZ states.

In particular, in Lamb-Dicke limit, it is not necessary to require the simultaneous clicks of detectors, which will relax the condition for practical realization.

Our schemes work in the same way as the proposal in Ref. [21], where the authors presented an idea to entangle two identical Λ -type three-level atoms with two degenerate ground states trapped in two separate cavities. We will first show that using different approaches the similar model can also be used to prepare GHZ and W states of distant atoms trapped in separate cavities in terms of simultaneous detections, and then emphasize that the simultaneous detections for our schemes are not necessary in Lamb-Dicke limit. Here we consider three identical Λ -type three-level atoms 1, 2 and 3 trapped, respectively, in three spatially separate optical cavities A , B and C which are all one sided. Every atom has an excited state $|e\rangle$ and two degenerate ground states $|g_l\rangle$ and $|g_r\rangle$. The transitions $|e\rangle \rightarrow |g_l\rangle$ and $|e\rangle \rightarrow |g_r\rangle$ are strongly coupled to left- and right-circularly polarizing cavity modes respectively. The photons leaking out of every cavity first transmit a quarter wave plate (QWP), and then pass through two different setups: One is to prepare GHZ state (See Fig. 1 (a)) and the other is for the preparation of W state (See Fig. 1 (b)). As shown in Fig. 1 (a), there are six detectors denoted by D_i^j with $i = a, b, c$ and $j = F, S$. If any three detectors with different subscripts are simultaneously clicked, one will obtain the GHZ states denoted by $|GHZ\rangle_{\pm} = \frac{1}{\sqrt{2}}(|g_l\rangle_1 |g_l\rangle_2 |g_l\rangle_3 \pm |g_r\rangle_1 |g_r\rangle_2 |g_r\rangle_3)$. If the three clicked D_i^j s correspond odd number of F (superscript), one will obtain $|GHZ\rangle_+$, otherwise, $|GHZ\rangle_-$. Analogously, in Fig. 1 (b), if any three detectors are clicked, one will obtain the W state, which consists of two cases: When both detectors corresponding to BS2 are clicked, one will obtain $|W\rangle = \frac{1}{\sqrt{3}}(|g_l\rangle_1 |g_l\rangle_2 |g_r\rangle_3 + |g_l\rangle_1 |g_r\rangle_2 |g_l\rangle_3 + |g_r\rangle_1 |g_l\rangle_2 |g_l\rangle_3)$, otherwise, $|\tilde{W}\rangle = \frac{1}{\sqrt{3}}(|g_l\rangle_1 |g_r\rangle_2 |g_r\rangle_3 + |g_r\rangle_1 |g_r\rangle_2 |g_l\rangle_3 + |g_r\rangle_1 |g_l\rangle_2 |g_r\rangle_3)$ will be obtained.

In the following we will illustrate our approach explicitly. The interaction Hamiltonian governing the interaction between the trapped Λ -type atoms and cavities is

*Electronic address: hssong@dlut.edu.cn

given by $H_I = \hbar \sum_{k=l,r} \lambda_k (a_k |e\rangle \langle g_k| + a_k^\dagger |g_k\rangle \langle e|)$, where l, r denoted the left- and right-circularly polarizing cavity modes, a_k^\dagger and a_k are the creation and annihilation operators of photons in the k mode, and λ_k , supposed to be real, is the coupling constant between the atom and the k mode. If the atom and the cavity are initially prepared in the excited state $|e\rangle$ and the vacuum state $|0_l\rangle |0_r\rangle$, respectively, after the interaction time t , the total system of atom and cavity will evolve to the state

$$|\Psi(t)\rangle = \cos \Omega t |e\rangle |0_l\rangle |0_r\rangle - i \sin \Omega t |\phi(t)\rangle, \quad (1)$$

with $|\phi(t)\rangle = \frac{1}{\Omega} (\lambda_l |g_l\rangle |1_l\rangle |0_r\rangle + \lambda_r |g_r\rangle |0_l\rangle |1_r\rangle)$ and $\Omega = \sqrt{\lambda_l^2 + \lambda_r^2}$ supposed to be a given constant. When photons are passing through the QWP, circularly polarizing photons become linearly polarizing. Analogous to Ref. [21], we suppose the left- and right-circularly polarizing photons correspondingly become vertically (denoted by V) and horizontally (H) polarizing, i.e. $|1_l\rangle |0_r\rangle \rightarrow |V\rangle$ and $|0_l\rangle |1_r\rangle \rightarrow |H\rangle$. Furthermore, because the vacuum state has no contribution to the click of the photodetectors, the term $|e\rangle |0_l\rangle |0_r\rangle$ in eq. (1) can be safely neglected for simplification. Therefore, when photon passing through the QWP, the total state of photon and atom can be written by

$$|\psi(t)\rangle = \frac{1}{\Omega} (\lambda_l |g_l\rangle |V\rangle + \lambda_r |g_r\rangle |H\rangle), \quad (2)$$

associated with a probability $P_1 = \sin^2 \Omega t$. Later it implies that photons have passed through QWP if we say photons leak out of cavities.

GHZ states- See Fig. 1 (a). Photons leaking out of cavity B and C will first meet PBS1 which always transmits H -polarizing photons and reflects V -polarizing photons (all PBS in the paper work in this way), hence the input modes $|V\rangle_B, |H\rangle_B$ will correspondingly change to the output modes $|V\rangle_d, |H\rangle_c$, and $|V\rangle_C, |H\rangle_C \rightarrow |V\rangle_c, |H\rangle_d$. Thus the joint state including cavities B, C and atoms 1, 2 will become

$$\begin{aligned} & \frac{1}{2} (|g_l\rangle_2 |V\rangle_B + |g_r\rangle_2 |H\rangle_B) \otimes (|g_l\rangle_3 |V\rangle_C + |g_r\rangle_3 |H\rangle_C) \\ \rightarrow & \frac{1}{2} (|g_l\rangle_2 |g_l\rangle_3 |V\rangle_d |V\rangle_c + |g_l\rangle_2 |g_r\rangle_3 |V\rangle_d |H\rangle_c \\ & + |g_r\rangle_2 |g_l\rangle_3 |H\rangle_c |V\rangle_c + |g_r\rangle_2 |g_r\rangle_3 |H\rangle_c |H\rangle_d) \\ \rightarrow & \frac{1}{\sqrt{2}} (|g_l\rangle_2 |g_l\rangle_3 |V\rangle_d |V\rangle_c + |g_r\rangle_2 |g_r\rangle_3 |H\rangle_c |H\rangle_d), \end{aligned} \quad (3)$$

where we suppose $\lambda_l = \lambda_r$ for GHZ state. As mentioned above, GHZ state requires that both modes c and d are not idle, otherwise one of the required detectors can not be clicked, hence we have discarded the bunching outcome in eq. (3) and preserved the antibunching outcome with the probability $P_2 = 50\%$ (We discard the bunching outcome just for simplification, one can not do so which will lead to the same result). Then the photon of mode d and that leaking out of cavity A will meet PBS2, which can lead to the following transformation between input

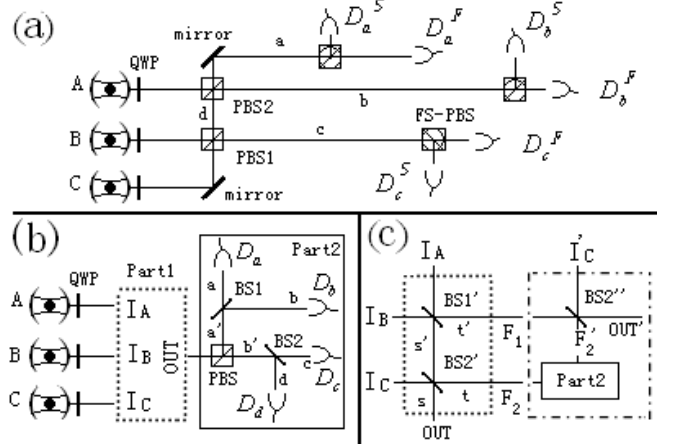


FIG. 1: (a) Experimental setup for GHZ states. After transmitting quarter wave plates (QWP), photons leaking out of cavities pass through the polarizing beam splitters (PBS) and rotated PBS (FS-PBS) and then are detected by photodetectors. (b) Experimental setup for W states. The setup includes Part1, bunching system and Part2, detection system. Entering port "I_i" $i = A, B, C$ and bunched out of port "OUT", photons pass through PBS and 50/50 beam splitters (BS) and then are detected by photodetectors. (c) The expanded setups for (b). Dotted box of (c) sketches an alternate scheme for Part1, where photons passing through two 50/50 BS are bunched via port "OUT". "F₁" and "F₂" are two expanded ports to improve the success probability, which can be connected with the dash-dotted box to double the efficiency of (b). In the dash-dotted box auxiliary atom 3' and cavity C' are introduced via the port "I'_C". Thus BS2' and BS2' become two symmetric arms of BS1'.

modes and output modes: $|V\rangle_d, |H\rangle_d \rightarrow |V\rangle_b, |H\rangle_a$ and $|V\rangle_A, |H\rangle_A \rightarrow |V\rangle_a, |H\rangle_b$. As a result, the joint state of the whole system (three atoms and three cavity modes) follows that

$$\begin{aligned} & \frac{1}{2} (|g_l\rangle_1 |V\rangle_A + |g_r\rangle_1 |H\rangle_A) \\ & \otimes (|g_l\rangle_2 |g_l\rangle_3 |V\rangle_d |V\rangle_c + |g_r\rangle_2 |g_r\rangle_3 |H\rangle_c |H\rangle_d) \\ \rightarrow & \frac{1}{\sqrt{2}} (|g_l\rangle_1 |g_l\rangle_2 |g_l\rangle_3 |V\rangle_a |V\rangle_b |V\rangle_c \\ & + |g_r\rangle_1 |g_r\rangle_2 |g_r\rangle_3 |H\rangle_a |H\rangle_b |H\rangle_c), \end{aligned} \quad (4)$$

where we only preserve the antibunching outcome with the probability $P_3 = 50\%$ for the same reason. At last, the three photons with different modes will, respectively, meet three rotated polarizing beam splitters (FS-PBS), which change $|H\rangle_i$ and $|V\rangle_i, i = a, b, c$ into a new frame as $|H\rangle_i = \frac{1}{\sqrt{2}} (|F\rangle_i - |S\rangle_i)$ and $|V\rangle_i = \frac{1}{\sqrt{2}} (|F\rangle_i + |S\rangle_i)$ and always reflect S -polarizing photons and transmit F -polarizing photons. In the new frame, the state given in

eq. (4) can be written by

$$\sum_{X,Y,Z=F,S} \frac{(|g_l\rangle_1 |g_l\rangle_2 |g_l\rangle_3 \pm |g_r\rangle_1 |g_r\rangle_2 |g_r\rangle_3) |X\rangle_a |Y\rangle_b |Z\rangle_c}{\sqrt{2}}, \quad (5)$$

where odd number of F among X, Y, Z corresponds to "+", otherwise, "-". Therefore, if three detectors of different mode of a, b and c are clicked simultaneously, the distant atoms 1, 2 and 3 will collapse to one of the GHZ states $|GHZ\rangle_{\pm} = \frac{1}{\sqrt{2}}(|g_l\rangle_1 |g_l\rangle_2 |g_l\rangle_3 \pm |g_r\rangle_1 |g_r\rangle_2 |g_r\rangle_3)$. The maximal probability of getting the state is given by $P_{GHZ} = (P_1)^3 P_2 P_3 = \sin^6 \Omega t \times 50\% \times 50\% = 25\%$ with $\sin^6 \Omega t = 1$.

W state—Let us turn to Fig. 1 (b). At first, we suppose three photons leaking out of the three cavities can be directly bunched. An alternate scheme will be presented later to bunch the three photons. As a result, when the three photons are transmitted out of the output port "OUT", the joint state of the whole system is

$$\bigotimes_{i=1}^3 \frac{1}{\Omega} (\lambda_l |g_l\rangle_i |V\rangle + \lambda_r |g_r\rangle_i |H\rangle) \quad (6)$$

where we have discard the subscripts of cavity modes, because one can not determine which cavity a photon comes from due to the indistinguishability of photons. Then they will meet PBS1 which will transform the input modes to the output modes as $|V\rangle \rightarrow |V\rangle_{a'}$ and $|H\rangle \rightarrow |H\rangle_{b'}$. Thus the state given by eq. (6) becomes

$$\begin{aligned} & \frac{1}{\Omega^3} \left[\lambda_l^3 |g_l\rangle_1 |g_l\rangle_2 |g_l\rangle_3 |3\rangle_{a'}^V + \lambda_r^3 |g_r\rangle_1 |g_r\rangle_2 |g_r\rangle_3 |3\rangle_{b'}^H \right. \\ & + \lambda_l^2 \lambda_r (|g_l\rangle_1 |g_l\rangle_2 |g_r\rangle_3 + |g_l\rangle_1 |g_r\rangle_2 |g_l\rangle_3 \\ & + |g_r\rangle_1 |g_l\rangle_2 |g_l\rangle_3) |2\rangle_{a'}^V |1\rangle_{b'}^H + \lambda_l \lambda_r^2 (|g_l\rangle_1 |g_r\rangle_2 |g_r\rangle_3 \\ & + |g_r\rangle_1 |g_l\rangle_2 |g_r\rangle_3 + |g_r\rangle_1 |g_r\rangle_2 |g_l\rangle_3) |2\rangle_{b'}^H |1\rangle_{a'}^V, \end{aligned} \quad (7)$$

where $|2\rangle_{a'}^V |1\rangle_{b'}^H = |V\rangle_{a'} |V\rangle_{a'} |H\rangle_{b'}$ with superscripts denoting polarizing modes and subscripts denoting output port modes. Finally, the photons will pass through two 50/50 beam splitters BS1 and BS2 which will transform $|1\rangle_{a'}^V$ and $|1\rangle_{b'}^H$ to the final detecting modes as $|1\rangle_{a'}^V \rightarrow \frac{1}{\sqrt{2}}(|1\rangle_a^V + i|1\rangle_b^V)$ and $|1\rangle_{b'}^H \rightarrow \frac{1}{\sqrt{2}}(|1\rangle_c^H - i|1\rangle_d^H)$. Hence we have the following transformations:

$$\begin{aligned} |2\rangle_{a'}^V |1\rangle_{b'}^H & \rightarrow \frac{1}{2\sqrt{2}} \left(|2\rangle_a^V |1\rangle_c^H - |2\rangle_b^V |1\rangle_c^H + 2i|1\rangle_a^V |1\rangle_b^V |1\rangle_c^H \right. \\ & \left. - i|2\rangle_a^V |1\rangle_d^H + i|2\rangle_b^V |1\rangle_d^H + 2|1\rangle_a^V |1\rangle_b^V |1\rangle_d^H \right) \end{aligned} \quad (8)$$

and

$$\begin{aligned} |2\rangle_{b'}^H |1\rangle_{a'}^V & \rightarrow \frac{1}{2\sqrt{2}} \left(|2\rangle_c^H |1\rangle_a^V - |2\rangle_d^H |1\rangle_a^V - 2i|1\rangle_c^H |1\rangle_d^H |1\rangle_a^V \right. \\ & \left. + i|2\rangle_c^H |1\rangle_b^V - i|2\rangle_d^H |1\rangle_b^V + 2|1\rangle_c^H |1\rangle_d^H |1\rangle_b^V \right). \end{aligned} \quad (9)$$

Substitute the two transformations into eq. (7), eq. (7) can be written in terms of the detecting modes of photons. If no two photons are allowed to click the same

detector, the terms where different detectors are clicked can be given by

$$\begin{aligned} & \frac{\lambda_l}{\sqrt{2}\Omega} |W\rangle \left(i|1\rangle_a^V |1\rangle_b^V |1\rangle_c^H + |1\rangle_a^V |1\rangle_b^V |1\rangle_d^H \right) \\ & + \frac{\lambda_r}{\sqrt{2}\Omega} |\tilde{W}\rangle \left(|1\rangle_c^H |1\rangle_d^H |1\rangle_b^V - i|1\rangle_c^H |1\rangle_d^H |1\rangle_a^V \right) \end{aligned} \quad (10)$$

The probability of getting such a state from eq. (7) can be given by $P' = \left| \frac{\sqrt{3}\lambda_l\lambda_r\Omega}{\Omega^3} \right|^2 \times \frac{2}{3} = \frac{2\lambda_l^2\lambda_r^2}{\Omega^4}$, where one should first normalize eq. (8) and eq. (9). From eq. (10) a W -class state can always be obtained if three detectors have been simultaneously clicked. If the three clicked detectors include D_a and D_b , one will obtain $|W\rangle$, otherwise $|\tilde{W}\rangle$. The maximal probability of getting W states is $\tilde{P}_W = (P_1)^3 P' = 2\sin^6 \Omega t \frac{\lambda_l^2\lambda_r^2}{\Omega^4} = \frac{1}{2}$ in terms of $\sin^6 \Omega t = 1$ and $\lambda_l = \lambda_r$.

Now we present an alternate scheme sketched as Fig. 1 (c) to bunch the three photons. Following Fig. 1 (c), one can find that when the two photons leaking out of cavities A and B pass through BS1', the joint state $\frac{1}{\Omega^2} (\lambda_l |g_l\rangle_1 |V\rangle_A + \lambda_r |g_r\rangle_1 |H\rangle_A) \otimes (\lambda_l |g_l\rangle_2 |V\rangle_B + \lambda_r |g_r\rangle_2 |H\rangle_B)$ will be transformed to the following non-normalized state

$$\begin{aligned} & \frac{1}{2} (|\Psi\rangle_{t'} + |\Psi\rangle_{s'}) + i \frac{\lambda_l \lambda_r}{2\Omega^2} (|g_l\rangle_1 |g_r\rangle_2 - |g_r\rangle_1 |g_l\rangle_2) \\ & \times \left(|1\rangle_{s'}^V |1\rangle_{t'}^H - |1\rangle_{t'}^V |1\rangle_{s'}^H \right), \end{aligned} \quad (11)$$

with $|\Psi\rangle_i = \frac{1}{\Omega^2} (\lambda_l^2 |g_l\rangle_1 |g_l\rangle_2 |2\rangle_i^V + \lambda_r^2 |g_r\rangle_1 |g_r\rangle_2 |2\rangle_i^H + \lambda_l \lambda_r |g_l\rangle_1 |g_r\rangle_2 |2\rangle_i^{V,H} + \lambda_l \lambda_r |g_r\rangle_1 |g_l\rangle_2 |2\rangle_i^{V,H})$, $i = s', t'$ being the initial joint state before inputting BS1. It is obvious that the state can collapse to $|\Psi\rangle_i$ bunching in the output port t' with the probability $P_{t'} = \frac{\Omega^4}{2\Omega^4 + 4\lambda_l^2\lambda_r^2}$. By the same algebra, one can find that the joint state $|\Psi\rangle_i \otimes \frac{1}{\Omega} (\lambda_l |g_l\rangle_3 |V\rangle + \lambda_r |g_r\rangle_3 |H\rangle)$ can collapse to itself (given in eq. (6)) bunching in the final port "OUT" with the probability $P_s = \frac{\Omega^4}{2\Omega^4 + 8\lambda_l^2\lambda_r^2}$. In this case the maximal probability of getting W states is $P_{W1} = P' P_{t'} P_s = \frac{\Omega^4}{2\Omega^4 + 4\lambda_l^2\lambda_r^2} \cdot \frac{\Omega^4}{4\Omega^4 + 8\lambda_l^2\lambda_r^2} \cdot \frac{2\lambda_l^2\lambda_r^2}{\Omega^4} = \frac{1}{36}$ with $\lambda_l = \lambda_r$, $P_{t'} = \frac{1}{3}$, $P_s = \frac{1}{6}$. In fact, one can also find that the joint state of the whole system can be bunched via the port "F2" with the same probability to P_s . Hence, if we connect "F2" with the same setup depicted as "Part 2" in Fig. 1 (b), the probability P_{W1} is doubled. Analogously, one can find that the initial joint state before BS1 can be bunched via the port "F1" with probability $P_{t'}$. If we introduce an auxillary atom $3'$ trapped in cavity C' connected with the input port I'_C , one can finally obtain the W states of atoms A, B and C' (denoted by W') by the setup depicted in the dot-dashed box of Fig. 1 (c). Both setups with and without "prime" are completely identical. Hence, from the viewpoint of the yield of W states, the doubled probability P_{W1} should be doubled

again. Thus the total probability of getting W states is $\frac{1}{36} \times 4 = \frac{1}{9}$. Compared with the preparation of the W states [16] of photons, our probability is higher (than $\frac{3}{32}$).

Both schemes emphasize the simultaneous clicks of detectors. The key is in that the spirit of our schemes is the indistinguishability. Because absorption or emission of photons will lead to a recoil of the atom, which will signal the atom [22], the indistinguishability is destroyed and lead to no entanglement. However, if our trapped atoms are restricted to operating in the Lamb-Dicke limit, where the recoil energy does not suffice to change the atomic motional state [22], the indistinguishability can be preserved and it is not necessary to require the simultaneous clicks. This in fact dramatically simplifies the practical operations. To test the validity, one can first suppose the clicked order of the detectors (such as $D_a^j \rightarrow D_b^j \rightarrow D_c^j$ and so on which must have different subscripts), and then follow the analogous procedures given above. In this way, so long as the clicked detectors are the same to those shown by simultaneous detections, one can obtain the same state (We have tested all the cases).

Here let us briefly discuss the robustness of our schemes. The scheme for GHZ state needs $\lambda_l = \lambda_r$, otherwise the final state $|\Phi\rangle$ will deviate from $|GHZ\rangle$. In fact, if $\lambda_l/\lambda_r = 1.1$, the fidelity is $|\langle\Phi|GHZ\rangle|^2 > 0.98$, which shows slight influence. But from above derivation for W states, one can find that different λ_l and λ_r only reduce the efficiency, while the fidelity is not influenced at all. One can also find that the 50/50 beam splitters are employed in the scheme for W states. If the beam splitters reflect and transmit photons without equal amplitudes, it is surprising that only the final efficiency is reduced, but the fidelity can not be changed. What is more, there exist the following four negative effects: (a) Not all the atoms are initially prepared in their excited states; (b) Some photons emitting to the free modes can not be detected; (c) Dark counts of the detectors, or some photons

are absorbed by cavity walls, even optical elements; (d) Photons are not leaked out simultaneously. However, (a-c) can not lead to *three* clicked detectors, and (d) will not make the desired three detectors clicked simultaneously. Therefore, all the cases can be effectively ruled out with the fidelity of the desired states invariant but sacrificing the preparation efficiency. However, in Lamb-Dicke limits besides that (a-c) can be ruled out analogously, (d) gives a positive contribution to the efficiency. Considering the cavity decay and atomic spontaneous emission which reduce the efficiency, the same discussions to those in Ref. [21] are valid, which is not repeated here.

In experimental scenario, our atomic level structure can be achieved by Zeeman sublevels [24] and has been realized to entangled two atoms [25]. What we used also consists of linear optical elements, and photon detectors, which has been widely used to entangle photons. In particular, the similar optical setups has been used to successfully prepare W states of photons in experiment [17]. Therefore, our schemes are feasible by current technologies.

In conclusion, we have proposed two schemes to prepare GHZ states and W states of distant atoms, respectively, based on the indistinguishability of photons emitted by the atoms. Our schemes are robust against the detection inefficiency, the asynchronous emission of photons. In particular, in Lamb-Dicke limit it is not necessary to require simultaneous click of the detectors, which will relax the requirement on the physical realization. The schemes are feasible by current technologies. They can readily be generalized to entangle multipartite distant atoms in principle, but the efficiency would be reduced.

This work was supported by the National Natural Science Foundation of China, under Grant No. 10575017 and No. 60578014.

-
- [1] A. K. Ekert, Phys. Rev. Lett. **67**, 661 (1991).
 - [2] C.H. Bennett and S.J. Wiesner, Phys. Rev. Lett. **69**, 2881 (1992).
 - [3] C. H. Bennett, G. Brassard, C. Crepeau, R. Jozsa, A. Peres, and W. Wootters, Phys. Rev. Lett. **70**, 1895 (1993).
 - [4] W. Dür, G. Vidal, and J. I. Cirac, Phys. Rev. A **62**, 062314 (2000).
 - [5] D. M. Greenberger *et al.*, Am. J. Phys. **58**, 1131 (1990).
 - [6] A. Karlsson and M. Bourennane, Phys. Rev. A **58**, 4394 (1998).
 - [7] B. S. Shi and A. Tomita, Phys. Lett. A, **296**, 161 (2002).
 - [8] R. Cleve, D. Gottesman, and H. K. Lo, Phys. Rev. Lett. **83**, 648 (1999); M. Hillery, V. Bužek, and A. Berthiaume, Phys. Rev. A **59**, 1829 (1999).
 - [9] J. Kempe, Phys. Rev. A **60**, 910 (1999); G. A. Dukin, C. Simon, and D. Bouwmeester, quant-ph/0109132.
 - [10] V. N. Gorbachev *et al.*, quant-ph/0203028.
 - [11] V. Bužek, M. Hillery, Phys. Rev. A **54**, 1844 (1996); V. Bužek *et al.*, *ibid.* **55**, 3327 (1997); V. Bužek *et al.*, *ibid.* **56**, 3446 (1997); D. Bruß *et al.*, *ibid.* **57**, 2368 (1998); M. Murao *et al.*, *ibid.* **59**, 156 (1999); N. Gisin *et al.*, M. Massar, Phys. Rev. Lett. **79**, 2153 (1997).
 - [12] X. B. Zou *et al.*, Phys. Rev. A **66**, 044302 (2002); X. B. Zou *et al.*, Phys. Rev. A **68**, 024302 (2003); X. B. Zou *et al.*, Phys. Rev. A **69**, 052314 (2004).
 - [13] C. D. Fidio *et al.*, J. Opt. B: Quantum Semiclass. Opt. **5**, 105 (2003).
 - [14] L. -M. Duan, H. J. Kimble, Phys. Rev. Lett. **90**, 253601 (2003).
 - [15] H. Mikami *et al.*, Phys. Rev. A **70**, 052308 (2004). Y. C. Ou *et al.*, quant-ph/0509069, and references therein.
 - [16] T. Yamamoto *et al.*, Phys. Rev. A **66**, 064301 (2002).
 - [17] M. Eibl *et al.*, Phys. Rev. Lett. **92**, 077901 (2004).
 - [18] D. Leibfried *et al.*, Nature **438**, 639 (2005).
 - [19] H. Häffner *et al.*, Nature **438**, 643 (2005).

- [20] A. Rauschenbeutel *et al.*, Science, 288, 2024 (2000).
- [21] Xun-Li Feng *et al.*, Phys. Rev. Lett. **90**, 217902 (2003).
- [22] C. Cabrillo *et al.*, Phys. Rev. A **59**, 1025 (1999).
- [23] S. Bose *et al.*, Phys. Rev. Lett. **83**, 5158 (1999); C. Simon, W. T. M. Irvine, *ibid.* **91**, 110405 (2003).
- [24] W. Lange and H. J. Kimble, Phys. Rev. A **61**, 063817 (2000).
- [25] J. Hong and H. -W. Lee, Phys. Rev. Lett. **89**, 237901 (2002).